procedures for reimbursing firms for bid and proposal costs, it is impossible to tally the amount.3/

DEPARTMENT OF ENERGY

The Department of Energy (DOE) will spend an estimated $77 million in fiscal year 1987 for research on semiconductor manufacturing technology. The National Laboratories will spend $62 million, mostly on radiation hardening ($55 million). Research on photovoltaic energy accounts for another $15 million.4/

National Laboratories

The National Laboratories, with their highly qualified scientific personnel and specialized equipment, have a wide variety of projects of potential use to the semiconductor industry. Their largest efforts in semiconductor manufacturing, however, currently have few commercial applications because they concentrate on radiation-hardening semiconductors for space and weapons systems. In addition to the laboratories discussed below, others also have semiconductor research programs of varying commercial potential. This section discusses the largest programs.

Sandia. The National Laboratory at Sandia is spending an estimated $50 million on microelectronics processing and science in fiscal year 1987, with production of integrated circuits accounting for an additional $20 million. Between $15 million and $20 million of their research expenditures, however, is incurred on behalf of the military services, which reimburse them.

3. For further discussion of IR&D, see Congressional Research Service, "Defense-Related Independent Research and Development in Industry" (October 18, 1985).

4. Some radiation hardening R&D for the Department of Defense is performed by the National Laboratories. The funding is accounted for in the DoD programs discussed above and so is not included in these totals.

Despite a concentration on radiation hardening, which accounts for two-thirds of its budget, some of Sandia's research may play a role in commercial manufacturing of semiconductors. For example, Sandia developed techniques for selectively depositing tungsten and refractory metals on chips. Sandia originally needed the technology to overcome some of the limitations of radiation hardening.5/ As commercial devices have become more complex, they have hit similar limitations. Sandia therefore sponsored conferences for the U.S. semiconductor industry as well as foreign companies to discuss the technology of depositing tungsten. This year International Business Machines (IBM) has taken over the conference, which suggests, if only implicitly, the commercial usefulness of the technology. It is not possible, however, for CBO to determine how much of Sandia's R&D expenditures produces commercially useful technology.

Lawrence Berkeley Laboratory (LBL). The LBL spends roughly $3.8 million on semiconductor research that could be transferred to the industry within three to five years.6/ The laboratory has several collaborative relationships with semiconductor manufacturing companies to improve their manufacturing process. LBL has the facilities and personnel to work in such areas as advanced materials (including gallium arsenide) and on semiconductor processing science (including ion implantation and plasma etching). Scientists at LBL have developed the world's brightest X-ray beam source, now installed on the Stanford Synchrotron Radiation Laboratory, which, like the National Synchrotron Light Source (NSLS) at Brookhaven, can be used for lithographic experiments. LBL also has several lines of packaging research as well as several national user facilities, which

5. Sandia technicians could not heat the chips to very high temperatures once they laid down the insulating layers. (Devices are reheated to smooth out the surfaces. Devices that are made without the final heating thus have surfaces with peaks and valleys and steep cliffs.) Technicians at Sandia developed ways of raising selected valleys by depositing tungsten and other refractory metals. This method eliminated cliffs, which are often the site of metal fatigue and breaks that cause short circuits.

6. This estimate is derived by taking LBL's total operating budget of $155 million and apportioning part of it to semiconductor research in proportion to the number of semiconductor projects divided by the total number of projects. If semiconductor projects are especially costly or cheap, this estimate may be off.

operate like the NSLS (described below). Most prominent among these is the National Center for Electron Microscopy.7/

The Lawrence Berkeley Laboratory is also the future site of the advanced light sources (ALS). Building on the success of the National Synchrotron Light Source at Brookhaven, DOE has committed roughly $145 million, including $100 million in construction costs, to build the next generation of synchrotron at LBL. (Fiscal year 1987 costs are estimated to be $3.5 million.) After its completion in 1992, the new synchrotron's annual operating budget should be in the range of $20 million to $25 million. The ALS beam is 1,000 times brighter and more coherent than that of the NSLS, and its frequency can be tuned. Scientists connected with the project liken the NSLS to a flashlight and the ALS to a laser. At present, one-third of ALS use is slated for industry.

Brookhaven. The Department of Energy is spending $20.9 million in fiscal year 1987 at Brookhaven. The operating budget of the National Synchrotron Light Source (NSLS), which is located at Brookhaven, accounts for $17.5 million, and the rest is for facilities and capital improvements. NSLS officials attribute roughly 10 percent to semiconductor research.8/ Industrial and academic researchers use either the polarized X-ray beam or the ultraviolet beam at the NSLS, which allows experimenters to examine surfaces very closely. Manufacturers or users of semiconductors who are working at the NSLS include IBM, American Telephone and Telegraph, General Electric, and Xerox. Oil companies also use the NSLS in their research. Brookhaven is reported to be oversubscribed.

Companies pay a fee for using the NSLS; the NSLS pays only for running the synchrotron itself. Experimenters build their own facilities to use the X-ray beam and pay their own staff. In addition, unfunded experiments deemed technically worthy are assigned to one or another of the private facilities. NSLS provides the beams to users

7. For a more complete description of LBL semiconductor facilities, see Lawrence Berkeley Laboratory, Office for Planning and Development, *Semiconductor Research Capabilities at the Lawrence Berkeley Laboratory* (February 1987).

8. Using this percentage, an estimated $2.1 million is spent on semiconductor research. This estimate assumes that semiconductor research is, on average, as costly as other NSLS research.

at no cost on the condition that they publish their results. Proprietary researchers must pay a full-cost recovery charge of $384 per eight-hour shift.

Semiconductor manufacturers generally have a different use for the NSLS and synchrotrons than do other industries. In addition to examining surfaces, semiconductor makers may be able to use the X-ray beam in their manufacturing process. As integrated circuits become denser and more complicated, the size of the individual features shrinks. At feature sizes one-third the size of the latest generation of memory devices, X-rays may be needed as light sources for the photolithography phase in the semiconductor manufacturing process.

Brookhaven is a possible site for a new synchrotron light source for use in developing a commercial X-ray lithography machine. This proposal is now being discussed in the Congress, DOE, DoD, and the scientific community.

Other National Laboratories. The laboratory at Oak Ridge spends roughly $1.5 million on semiconductor research that involves direct collaboration with industry or that could be transferred to industry in three to five years. The research focuses on the Surface Modification and Characterization Center at Oak Ridge. The research in semiconductor processing includes laser-assisted deposition of chemical vapors, microwave plasma processing, direct ion beam deposition, and ion implantation for the production of buried insulating layers. Other projects at Oak Ridge may have useful applications to semiconductor manufacturing in the future. The general nature of these projects, however, makes it difficult to assess the usefulness of the research to any one industry.

The Lawrence Livermore National Laboratory is the site of significant research on the packaging of semiconductors. This work has been done over the last year using VHSIC and SDIO funds. The DOE has provided no special funds for semiconductor research at this facility. The research on packaging has focused on laser-assisted pantography. This process uses a computer-directed laser beam to locally induce chemical processes that either deposit, remove, or imbed desired chemicals on the silicon wafer to create circuits.9/ In one example of this procedure, the chip-to-board interconnects are chemically deposited down the edge of the IC die during the fabrication process, rather than attached afterward as is typically the case. The use of laser-assisted pantography allows chips to have very thin interconnects, which can be helpful in reducing the fraction of the die used for interconnection. Some specialized integrated circuits currently may have 150 or more individual interconnects.

The Ames and Argonne National Laboratories also have semiconductor research programs totaling $1 million a year.

Photovoltaic Research

The photovoltaic (PV) or solar cells, which power satellites, navigational buoys, and, increasingly, hand-held calculators, are actually semiconductor devices (diodes) that turn light into electricity. They are typically made of the same materials (silicon and gallium arsenide) as other semiconductor devices and often are made in the same general way as other discrete semiconductor devices, such as regular diodes or transistors. Thus, the DOE's effort to promote PV energy overlaps in several areas with commercial materials research. Such research will cost DOE $15 million in fiscal year 1987.

The Department of Energy's photovoltaic research might prove most helpful to commercial manufacturers of semiconductors by lowering the costs of materials. Photovoltaic cells use larger amounts of semiconductor materials than do other semiconductor devices.10/ Thus, DOE's research on photovoltaics has concentrated on producing large amounts of semiconductor-quality silicon cheaply and on simplifying the production of other semiconductor materials. One

9. Lawrence Livermore National Laboratory, *Laser Pantography: 1986 Status Report for the Very High Speed Circuit Program* (Livermore, Calif.: LLNL, February 1987).

10. Photovoltaic cells need to be larger than other devices because ultimately they are converting the sunlight that strikes them into electricity. The size of an object determines the amount of sunlight that strikes it; that is, a two-square-inch solar cell will receive twice as much sunlight as the one-inch solar cell next to it.

silicon manufacturing plant using technology developed in this program has already been built, and two more are planned or under construction.11/

One area of special interest is gallium arsenide on silicon (GaAs on Si) devices. This technology, in which a layer of GaAs is deposited on top of silicon substrate, promises to develop solar cells that can convert up to 30 percent of the energy they receive from the sun into electricity. (Conventional solar cells convert anywhere from 7 percent to 15 percent.)

The DOE's photovoltaic program is sponsoring research aimed at developing ways of manufacturing GaAs on Si, which is difficult. Conventional semiconductor manufacturing firms might gain from this technology. Working with silicon is at this point straightforward; large ingots of silicon can be grown, the silicon has mechanical strength, and it forms insulating oxides easily. However, silicon devices are slow, are difficult to use in lasers and light-emitting diodes (which are at the heart of fiberoptics), and operate only within limited temperature ranges. GaAs is the perfect complement to silicon. It is fast, can be made to emit light, and will operate at higher temperatures. Unfortunately, it lacks mechanical strength and is very hard to grow, and therefore is too expensive for most commercial uses. Thus, devices with the cost and mechanical properties of silicon and the electronic and optical properties of GaAs could find widespread use in faster computers, telecommunications, fiberoptics, and other areas.

NATIONAL SCIENCE FOUNDATION

National Science Foundation (NSF) officials estimate that they will sponsor roughly $30 million of semiconductor research in fiscal year 1987. Research into new semiconductor materials and techniques for laying down thin layers of semiconductor materials will cost $11 million. The Electrical Engineering Division of NSF is spending an

11. For a more complete description of DOE's photovoltaic research, see DOE, *Annual Progress Report: Photovoltaics FY 1986* (February 1987).

estimated $8.5 million to $10.0 million on the design of new devices. This includes research into lithography, resists, three-dimensional structures (very important in the next generation of devices), and superconducting devices. The Computer Directorate in NSF is sponsoring $5 million for the design of silicon devices, including computer software that would simplify the design of larger integrated circuits. Sponsorship of Engineering Research Centers will cost NSF $4 million.12/ This effort includes a center for optical semiconductor research at the University of Illinois and, at the University of California at Santa Barbara, a center for robotics to automate the manufacture of semiconductors. Finally, the Emerging Engineering Technologies Division will spend $1.5 million on optical-related devices.

NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards (NBS) concentrates on metrology, the science of measurement. In fiscal year 1987, NBS is projected to spend $3.9 million on semiconductor-related research, down from $5.1 million in 1983. Semiconductor research at NBS concentrates on four areas. The Materials Characterization Group develops, evaluates, and documents improved techniques for measuring materials defects and impurities in semiconductors, with a special project to extend many of the measurement techniques now used in silicon to GaAs. The Semiconductor Process Metrology Group does the same thing for IC processing techniques, such as measuring the dimensions of different patterned layers in the integrated circuits. The Semiconductor Device Technology Group determines critical parameters for analyzing and predicting how a semiconductor device will operate. The Integrated Circuit Technology Group develops test

12. For details, see National Research Council, Commission on Engineering and Technical Systems, *The Engineering Research Centers: Leaders in Change* (Washington, D.C.: National Academy Press, 1987), especially Susan Hackwood, "Center for Robotics in Microelectronics," pp. 61-72.

structures and methods for very-large-scale integrated circuits whose complexity makes thorough testing impractical.13/

INCREMENTAL R&D TAX CREDIT

A tax credit is available to corporations that increase their qualified R&D expenses above the average of the previous three years. The amount of the credit is equal to 25 percent of the difference between the three-year average and the current year.14/ Current projections indicate that the credit will cost the Treasury about $1.8 billion in fiscal year 1987.15/

Since semiconductor firms have been increasing their R&D spending, many have undoubtedly been eligible for the credit. Eligibility for receiving the credit is not reported on a desegregated basis, however, and some method of prorating the credit must be used to calculate the amount of the credit going to semiconductor research efforts. Depending on the method used, between $50 million and $100 million of the revenue loss attributable to the credit would go to semiconductor research. All methods suffer from major weaknesses, however, and any estimate should be regarded as an order of magnitude.16/

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13. For a fuller description of this work, see National Bureau of Standards, "Semiconductor Electronics Division Functional Statement" (no date). See also, NBS Planning Report 8, *Productivity Impacts of NBS R&D: A Case Study of the NBS Semiconductor Technology Program* (June 1981).

14. For a substantive discussion of the credit, see Congressional Budget Office, *Federal Financial Support for High-Technology Industries* (June 1985), pp. 21-25 and 58-65.

15. Office of Management and Budget, *Special Analyses of the Budget of the United States Government, Fiscal Year 1988*, p. G-42.

16. The method that produced the lower estimate uses the 1983 Statistics of Income data to calculate the electronic components industry's share of the 1983 total credit and then, using value added, calculates the semiconductor industry's share of that credit. Obviously, semiconductor research may have grown at a very different rate than overall research and may not conform to the 1983 share. The method yielding the higher estimate uses *Business Week* data to establish the percentage of corporate R&D performed by companies whose primary activity is semiconductor manufacturing (IBM, the world's largest semiconductor producer, and AT&T are therefore excluded). The distribution of the credit is then assumed to be proportional to the distribution of R&D. In fact, those industries that account for the bulk of R&D account for a greater amount of the increase. See National Science Foundation, *Research and Development in Industry, 1984* (Washington, D.C.: NSF, 1987), p. 23.

APPENDIX B

INTRODUCTION TO SEMICONDUCTORS

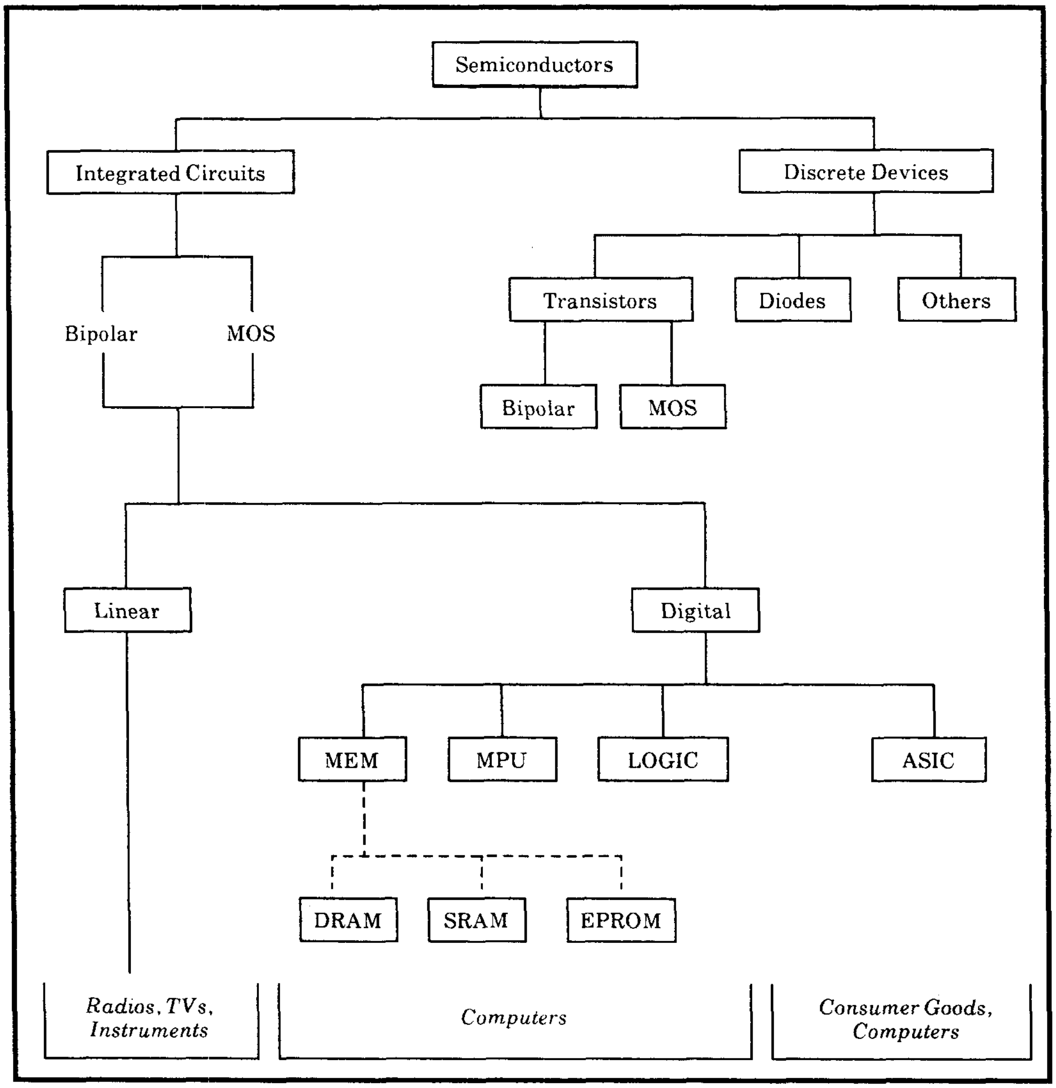
The semiconductor industry produces a variety of products that are all manufactured in a similar way. This appendix outlines the types of products and the manufacturing techniques used to produce them.

WHAT IS A SEMICONDUCTOR?

Semiconductor devices are the electronically active components, such as transistors and diodes, used in solid-state electronic goods. These devices are made of semiconducting material, which, as the name implies, is neither a good conductor nor a good insulator. Most semiconductor devices are made from silicon--essentially, purified sand. Like vacuum tubes before them, semiconductors control the electrical flows within electronic equipment. Semiconductor devices, however, are less bulky, consume less power, generate less heat, and are more reliable than vacuum tubes. Hence, they have largely supplanted vacuum tubes in all but a few applications and are used in most electronic goods. In 1984, roughly 40 percent of the semiconductors consumed in the United States were used in computers. The rest were roughly equally split among government, consumer, industrial, and communications applications. In Japan, consumer uses of semiconductors are much greater than those of the government and computers.

The different kinds of semiconductor devices are displayed in Figure B-1. The most common semiconductor components are diodes and transistors. When different individual components are joined together within a single device, this device is called an integrated circuit (IC) or, informally, a chip. Individual integrated circuits currently can have up to several hundred thousand individual components within them. About 80 percent of the value of worldwide semiconductor consumption is integrated circuits.

FIGURE B-1. PRINCIPAL TYPES OF SEMICONDUCTOR DEVICES



SOURCE: Adapted by Congressional Budget Office from Robert W. Wilson, Peter K. Ashton, and Thomas P. Egan, *Innovation, Competition, and Government Policy in the Semiconductor Industry* (Lexington, Mass.: D.C. Heath, 1980), p. 20.

NOTE: MOS = Metal-Oxide Semiconductor. MEM = Memory. MPU = Microprocessors. LOGIC = Standard Logic. ASIC = Application-Specific Integrated Circuit. DRAM = Dynamic Random Access Memory. SRAM = Static Random Access Memory. EPROM = Erasable Programmable Read Only Memory.

Integrated circuits can be made using either bipolar or metal-oxide semiconductor (MOS) transistors. Bipolar transistors use the whole semiconductor, whereas in MOS transistors the bulk of the effects occur on or near the surface. Because working only at the surface reduces the extent to which materials must be modified, MOS devices are typically easier to make and so tend to be denser.1/ MOS technology is often used to introduce new devices. Bipolar transistors tend to be faster, but are more complex and costly to manufacture.

The integrated circuit market can be further divided into linear and digital chips. Linear or analog circuits try to create an analog of the signal they are processing, whereas digital circuits reduce signals to a series of 0 and 1, which are then used to recreate or process the original signal. Analog circuits are used in communications equipment and instruments, while digital circuits are used primarily in computers. Digital chips account for over 80 percent of U.S. consumption of integrated circuits.2/ They can be used for memory, microprocessors, standard logic (such as that which connects microprocessors to other devices), and for very specific applications.

Within these broad categories, there are many different types of devices. For instance, memory devices can be generally divided into random access memory (RAM), which the user can read from and write to (commonly used in main computer memory); read only memory, which can only be read but not written to (used in many customized microprocessor applications); and other memory types, such as bubble memory and specialized input-output memory.3/

Random access memory is divided into dynamic RAM (DRAM) and static RAM (SRAM). DRAMs have more capacity but are slower

1. As MOS becomes denser, however, it is also changing and may become more three-dimensional. See Robert J. Kopp, "Recent Developments in Deposition and Doping and for Advanced ICs," in Semiconductor Materials and Equipment Institute *Forecast: The Business Outlook for the Semiconductor Equipment and Materials Industry, 1987-1989* (Mountain View, Calif.: SEMI, 1987), pp. 103-133.

2. *Electronics*, January 8, 1987, p. 69.

3. For a discussion of semiconductor memories, see David Hodges, "Microelectronic Memories," *Scientific American* (September 1977), pp. 130-145.

than SRAMs. In a state-of-the-art minicomputer, DRAMs are used for main computer memory, which may hold more than 16 million units (bytes) of information.4/ By contrast, the speed of SRAMs makes them useful in cache memory, a sort of electronic clipboard that keeps only those pieces of information to which quick access is needed. Cache memory is on the order of 32,000 to 128,000 bytes. This difference in demand for computer memory helps make the DRAM market much larger than the SRAM market.

DRAMs and SRAMs both come in different sizes, speeds, and configurations. The latest generation of DRAM can hold over 4 million bits (megabits, or Mb). But DRAMs are still made in smaller sizes--16,000 (K) bits, 64K bits, 256K bits, and 1 megabit. Because of their more complex circuitry, SRAMs have progressed no further than 256K. DRAMs are simpler and cheaper than SRAMs. A 256K DRAM currently costs $2.50 to $3.00, depending on the quantity desired; a 64K SRAM costs $12 to $20, depending on speed.5/

HOW ARE SEMICONDUCTORS MADE?

Most semiconductor devices are produced by taking silicon wafers that are usually 3 to 6 inches in diameter and chemically modifying them to create electronic pathways along predetermined courses on their surface. While the details of the process for making microprocessors may vary from that for making memories, there are enough similarities that the same production lines are commonly used for both, though not simultaneously. Production of semiconductors is largely a chemical manufacturing process, rather than a mechanical or electronic process.6/

4. A bit is a zero (0) or one (1) used in the binary language of computers. A byte is 8 bits.

5. "CMOS Memory Manufacturers Cracking the 15ns Barrier As They Rev Up Static RAMs for Microprocessor Market," *Electronic News*, July 13, 1987, p. 28. Part of the price differential also results from the competitive conditions in the particular market.

6. Discussion taken from David Elliott, *Integrated Circuit Fabricated Technology* (New York: McGraw-Hill, 1982).

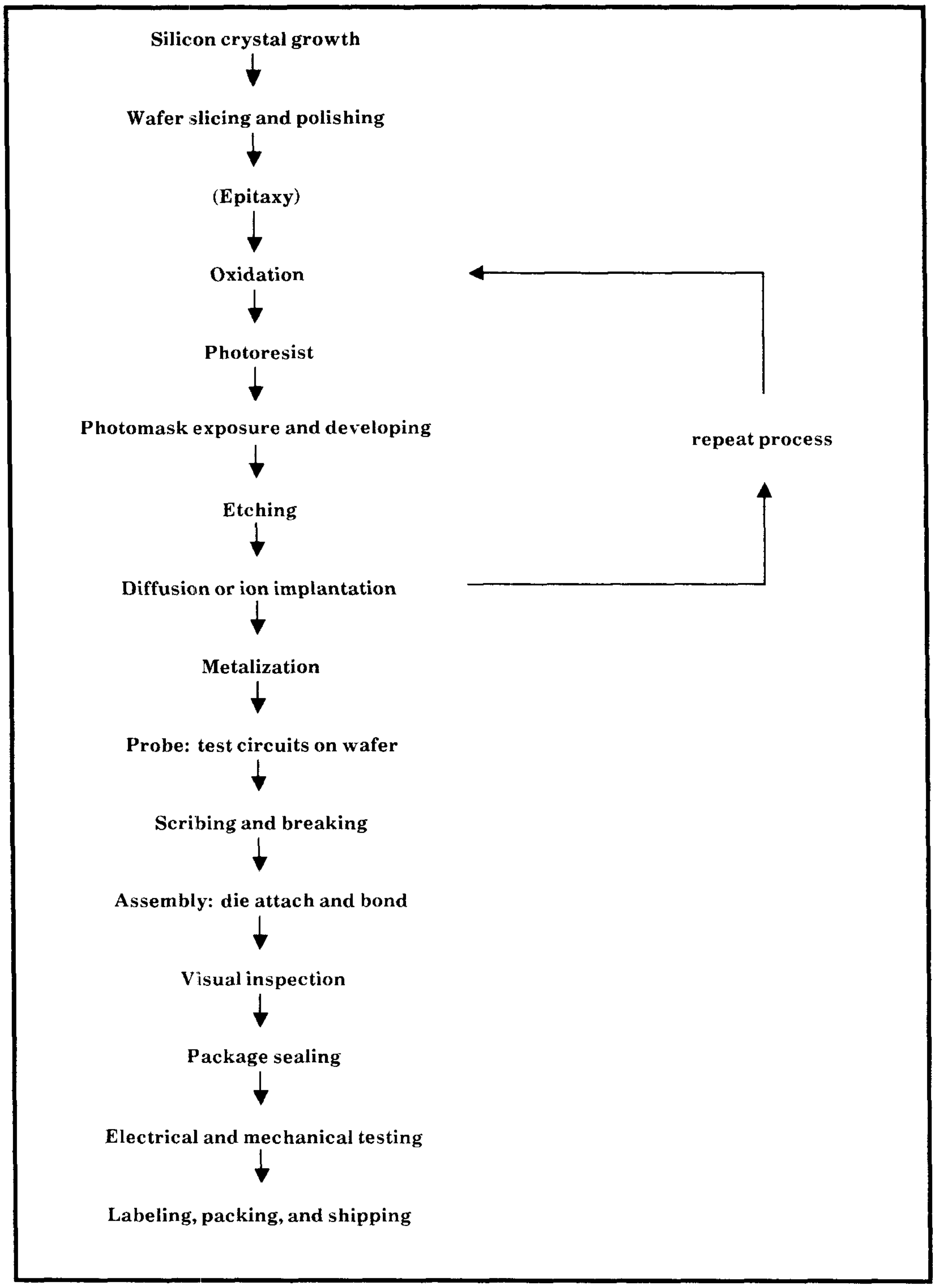
Figure B-2 shows the stages of the semiconductor manufacturing process. Manufacturers first take wafers of hyper-pure silicon and grow a layer of silicon dioxide on the top by placing the wafer in an oxidation oven. The oxide layer is then coated with a light-sensitive photoresist. A photographic image of one layer of the circuit to be manufactured is projected into the photoresist. This process is repeated until several hundred images of that one layer cover the entire wafer. When the photoresist has been developed, the defined parts of the circuit wash away, exposing the oxide layer underneath. The oxide is etched away, leaving the silicon open. This silicon is modified by introducing phosphorus or boron into its crystal structure, either through chemical deposition or ion implantation. These impurities create the unique electronic characteristics that give the chip its power. This entire process is repeated for every layer of the circuit. After the silicon layers have been laid down, the manufacturers deposit one or more layers of metal (usually aluminum) to provide interconnections.7/ Bonding pads are then laid for final assembly.

The completed circuits, hundreds to each wafer, are then tested. The automated testing equipment holds each wafer and sequentially tests and marks each of the hundreds of circuits on the wafer. After testing, the wafer is sawed into the individual devices. The circuits that pass testing are then packaged and sold.

The costs of integrated circuits are determined largely by the number that survive until the final test. Given the precision required in manufacture (alignments in millionths of an inch, contamination levels at the parts per million level), spoilage of both individual die and whole wafers is very common. For new devices, up to 85 percent and 90 percent of the die can fail the final test. Spoilage can be caused by a speck of dust, improper use of machines, or even the operators' cosmetics. The percentage of the chips that pass the test and can be used is called the yield; as the yield rises, costs fall. Thus, semiconductor firms are very yield-conscious and seek to enhance it.

7. It is this structure--having the metal on top of the oxide layer on top of the original silicon--that gives metal-oxide semiconductor devices their name. Bipolar devices are more complex.

FIGURE B-2. THE STAGES OF INTEGRATED CIRCUIT FABRICATION



SOURCE: Richard Levin, "The Semiconductor Industry," in Richard Nelson, ed., *Government and Technical Progress* (New York: Pergamon Press, 1982), p. 17.

Yields can be the difference between profit and loss for semiconductor companies and play a central role in the firm's planning. For example, in 1983 a wafer of 64K DRAMs contained an average of 313 integrated circuits and cost $120 to fabricate and test.8/ Packaging and final testing cost another $0.39 per chip. Using these average costs and assuming an average probe yield (that is, the percentage of usable devices that emerges from the wafer fabrication process) of 40 percent, one gets an average 64K DRAM cost of $1.93 per chip. If a firm had a probe yield of only 35 percent, there would be fewer integrated circuits to share the fabrication and testing costs of $120 per wafer, and so unit costs would rise to $2.14 per 64K DRAM. Conversely, by increasing the yield to 45 percent, unit costs would fall to $1.78 per 64K DRAM. Thus, by increasing yields from 35 percent to 45 percent, a firm could decrease unit costs by $0.36 per chip, or almost 20 percent. (See Figure B-3 for an illustration of the effects of different yields on the cost of DRAMs.) In a competitive industry like the semiconductor industry, this would be a substantial lead. Although data on yields are closely held by firms, one recent estimate suggested Japanese firms had a 65 percent advantage in the final yield of 64K DRAMs.9/

FUTURE DIRECTIONS IN SEMICONDUCTOR MANUFACTURING

The demand for increasingly powerful integrated circuits is influencing the planning for future semiconductor manufacturing technology. As integrated circuits become more complex and incorporate more devices, the minimum feature size shrinks. Smaller minimum feature sizes (or geometries, as they are also called) present greater problems for manufacturing; the requirements for controlling

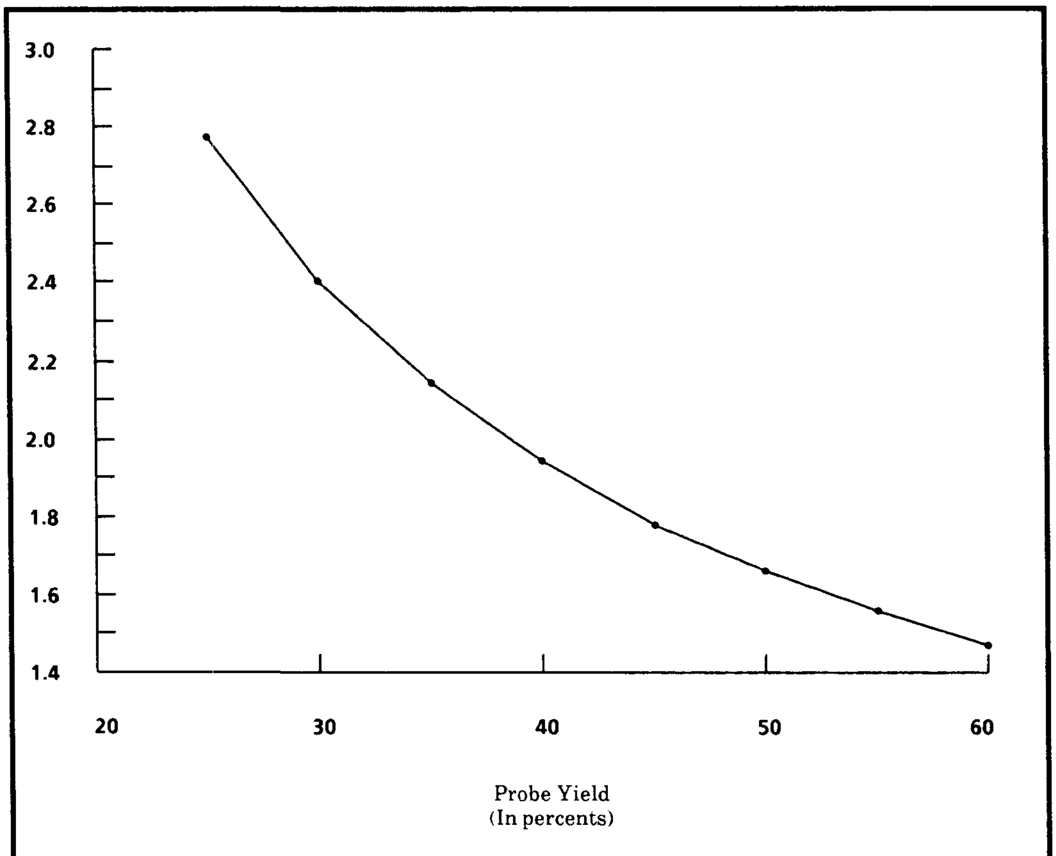
8. This example and calculations are from W. Edward Steinmueller, "Microeconomics and Microelectronics: Economic Studies of the Integrated Circuit Industry" (Ph.D. Dissertation, Stanford University, 1987), p. 197, citing Integrated Circuit Engineering, *Status 1983: A Report on the Integrated Circuit Industry* (Scottsdale, Arizona: ICE, 1983), p. 117.

9. William Finan and Annette LaMond, "Sustaining U.S. Competitiveness in Microelectronics: The Challenge to U.S. Policy," in Paul Krugman, ed., *Strategic Trade Policy and the New International Economics* (Cambridge, Mass: MIT Press, 1986), p. 156.

both the materials and the manufacturing process become much more stringent as the size of geometries decreases. Techniques, equipment, and materials that were useful at larger geometries no longer serve and may in fact become counterproductive. In short, virtually every piece of equipment and step of the process has to be rethought and redesigned to produce the ultra-large-scale integrated circuits of the future.

Smaller geometries, with less margin for error, require better equipment, and better circuits require better design. Thus, the trend

FIGURE B-3. EFFECT OF YIELDS ON THE COSTS OF 64K DRAMs
(In dollars per integrated circuit)



SOURCE: Calculated by Congressional Budget Office using data from W. Edward Steinmueller, "Microeconomics and Microelectronics: Economic Studies of Integrated Circuit Technology" (Ph.D. Dissertation, Stanford University, 1987), p. 195.

NOTES: Probe yield is the percentage of usable devices that emerge from the wafer fabrication process. DRAM = dynamic random access memory.

toward more powerful integrated circuits results in increasing capital and R&D expenditures by semiconductor producers and their suppliers. Lithography equipment that cost tens of thousands of dollars a decade ago now costs hundreds of thousands, and soon will cost millions of dollars per machine. The first microprocessor, for example, took Intel four man-years (on the order of several hundred thousand dollars) to develop.10/ By contrast, Intel's latest generation of that microprocessor reportedly cost roughly $100 million to develop. These changing capital requirements will affect the structure of the industry and its future direction.

10. Arthur Robinson, "Giant Corporations from Tiny Chips Grow," *Science* (May 2, 1980), p. 483.